Analysis of Ground-Measured and Passive-Microwave-Derived Snow Depth Variations in Midwinter across the Northern Great Plains

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ABSTRACT

Accurate estimation of snow mass is important for the characterization of the hydrological cycle at different space and time scales. For effective water resources management, accurate estimation of snow storage is needed. Conventionally, snow depth is measured at a point, and in order to monitor snow depth in a temporally and spatially comprehensive manner, optimum interpolation of the points is undertaken. Yet the spatial representation of point measurements at a basin or on a larger distance scale is uncertain. Spaceborne scanning sensors, which cover a wide swath and can provide rapid repeat global coverage, are ideally suited to augment the global snow information. Satellite-borne passive microwave sensors have been used to derive snow depth (SD) with some success. The uncertainties in point SD and areal SD of natural snowpacks need to be understood if comparisons are to be made between a point SD measurement and satellite SD. In this paper three issues are addressed relating satellite derivation of SD and ground measurements of SD in the northern Great Plains of the United States from 1988 to 1997. First, it is shown that in comparing samples of ground-measured point SD data with satellite-derived 25×25 km^2 pixels of SD from the Defense Meteorological Satellite Program Special Sensor Microwave Imager, there are significant differences in yearly SD values even though the accumulated datasets showed similarities. Second, from variogram analysis, the spatial variability of SD from each dataset was comparable. Third, for a sampling grid cell domain of $1° \times 1°$ in the study terrain, 10 distributed snow depth measurements per cell are required to produce a sampling error of 5 cm or better. This study has important implications for validating SD derivations from satellite microwave observations.

1. Introduction

With the continued growth in world population and industrial and commercial productivity, demands on global water resources have increased greatly. For effective water resources management there is a need to accurately quantify the various components of the hydrological cycle at different space and time scales. Snow is a renewable water resource of vital importance in large portions of the world and is one of the major hydrological cycle components. It is also a major source of water storage and runoff for many parts of the world. For example, in the western United States snow contributes over 70% of total water resources. To better predict snow storage and detect trends in the variations of water resources, accurate snowpack information with known error characteristics is necessary.

Traditionally, rulers, fixed snow stakes, and snow boards are used to measure the snow depth (SD) at a point. In general, point measurements of SD produce high quality data representative of a small location (<10 m scale length). To monitor SD in a temporally and spatially comprehensive manner, optimum interpolation of the points must be undertaken (Brasnett 1999; Brown et al. 2003). However, the spatial representativity of point measurements in a basin or at larger scale is uncertain (Atkinson and Kelly 1997). Furthermore, the spatial density of SD measurements in most parts of the world is rather low. Thus, the accuracy of spatially integrated point measurements of SD needs to be assessed carefully.

Spaceborne scanning microwave sensors, which cover a wide swath and can provide rapid repeat global coverage, are ideally suited to augmenting global snow measurements. For example, passive microwave radiometers such as the Scanning Multifrequency Microwave Radiometer (SMMR) on *Nimbus-7* and Seasat-A and the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager (SSM/I) have been utilized to retrieve global SD. To assess the representativity of satellite-derived SD, it is necessary to determine how and whether the point SD measurements can be compared with the spaceborne-derived SD that typically represents about 25×25 km^2 in area.

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The uncertainties in point and areal SD measurements of natural snowpacks need to be understood if comparisons are to be made between point SD measurements and satellite-derived SD. The statistical variability of the snow depth, as represented by the variogram, has a direct effect on the accuracy of SD derived from satellite data. Consequently, it is essential that the magnitude and cause of any variability is clearly defined for robust global validation of satellite-derived SD. In this paper we use sparsely distributed SD data from the National Weather Service (NWS) cooperative station network and SSM/I-derived SD data to study large-scale snow distribution.

To understand the snow-distribution characteristics from ground-measured SD, it is necessary to know the density of point SD measurements and the defined SD areal accuracy. Geostatistical analysis can be used to gain a better understanding of the spatial variability of snow depth in large areas, such as the northern Great Plains. Although there are large portions of the world where the spatial density of point-measured SD is less then 1 per 10 000 km^2 (approximately about the area of 1° latitude by 1° longitude), the aims of this study are to understand and quantify statistically the uncertainties associated with sparse sampling of SD over a regional scale, and to determine how these uncertainties affect the validation of global SD derivations from satellite observations at a local to regional scale. The aim of this study is to find out how well remote sensing–derived SD can be validated by current ground-measured point SD data, specifically

1) How well does ground-measured SD compare with satellite-derived SD?
2) What are the characteristics of snow spatial distribution?
3) What are the sampling criteria for making ground snow measurements so they can be used to validate satellite-derived SD, given a predefined accuracy requirement?

Throughout the paper we refer to ground SD, which refers to the measurement of snow depth at a point made by a temporary ruler or permanent ruled staff. The snow depth is the accumulated vertical thickness of snow from the ground to the snow–air interface at any given moment.

5. Summary and discussion

Ten years of ground SD data were used to evaluate the single SSM/I-footprint-derived SD for northern Great Plains snowfields during midwinter. From year to year comparisons, 8 out of 20 yr had significant differences between ground and SSM/I derived SD data. The mean ground SD for the 10-yr composite was 17.9 cm with a standard deviation 21.9 cm, while the SSM/I-derived SD was 18.3 cm with a standard deviation of 17.9 cm. The 10-yr mean difference between ground SD and SSM/I-derived SD was 0.4 cm, which is not statistically significant.

The variograms of ground SD and SSM/I derived SD were comparable. The absolute geostatistical range differences between ground SD and SSM/I SD is less than 500 km. In general, the ranges decreased as the snow depth increased, suggesting that for thinner snowpacks, the correlation lengths increase, while for thicker snowpacks they decrease. Also, the nugget variances were larger for thicker snowpacks, suggesting that there is more unresolved variation at each sample point when greater snow accumulations are present.

Comparisons of the $1° \times 1°$ latitude–longitude gridded data showed that the yearly differences of ground SD and SMM/I SD were not significant. The 10-yr composite mean and standard deviation of the ground SD was 17.7 and 19.7 cm, respectively, and the SSM/I-derived SD was 18.8 and 16.9 cm, respectively. The mean difference between ground and satellite-derived SD was 1.1 cm and was not significant. The standard deviation of the difference between ground and SSM/I SD was slightly smaller (16.1 cm) than the comparison for point data (18.7 cm).

For the composite mean of the 10-yr period, this research suggests that at the $1° \times 1°$ grid cell scale, SSM/I data can be used effectively to map snow depth in the NGP area. At the interannual time scale, however, there was both agreement and disagreement between ground and SSM/I-derived SD data. When the spatial density of ground SD measurements is increased, we suggest that snow depth spatial variability can be captured by the SSM/I retrieval algorithm and has a calculated error of 8.8 cm. In comparing the SSM/I data with ground measurements, the advantage of increasing the number of measurements sites within a grid cell is reported. The modeled sampling error curve of ground SD measurements is about 22 cm for 1 site, 7 cm for 10 sites, and for more than 10 sites less than 7 cm on a $1° \times 1°$ grid cell domain. This curve relating estimation error with number of measurements sites per cell shows that for the northern Great Plains area, the sampling error does not reduce quickly, even as the number of ground SD sites approaches 10. In the context of global snow depth estimates, this research demonstrates that it is rather difficult to quantify the global SD accuracy by using only the limited ground SD data where measurement-site density is often less than one per $1° \times 1°$ of latitude and longitude. Perhaps, therefore, the only way to use these spatially limited datasets is to scale up (average) both the passive microwave data and the ground measurements to a grid cell size that is in excess of $1° \times 1°$ of latitude and longitude. Even then, in certain parts of the world where ground data are very sparse, comprehensive validation of passive microwave estimates of snow depth may not be possible without a dedicated ground or aircraft field campaign.

The Advanced Microwave Scanning Radiometer (AMSR) was launched on board the Japanese *Advanced Earth Observing Satellite-II (ADEOS-II)* and the U.S. Earth Observation System (EOS) *Aqua* satellite in 2002. AMSR can provide the best ever spatial resolution multifrequency passive microwave radiometer observations from space [18-GHz channel instantaneous field of view (IFOV) is 27×16 km^2 and 36-GHz channel IFOV is 14×8 km^2]. This capability provides us with an opportunity to estimate surface snow mass quantities at finer spatial resolutions than have been possible with previous microwave instruments and so is an opportunity to improve snow depth observations both with respect to spatial resolution and accuracy of retrieval. However, for field experiments designed to test satellite observations, the ground-sampling network requires careful planning to ensure snow cover parameters such as SD are accurately measured.